MEMORANDUM REPORT ARBRL-MR-03341

A THREE-DEGREE-OF-FREEDOM FLIGHT SIMULATOR FOR SPIN-STABILIZED PROJECTILES

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March 1984

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (bja)

A three-degree-of-freedom flight simulator has been constructed to model the free-flight angular motion of spin-stabilized projectiles. Hydraulic actuators are used to drive a conventional gimbal system producing pitch and yaw, while an electric motor yields steady roll rates as fast as 200 Hz.

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I. INTRODUCTION

Modern spin-stabilized projectiles typically carry submunition systems, payloads with loose parts, or liquid-filled canisters. These types of payloads if not properly designed can interact with the normally stable motion of the projectile and result in dramatic flight instabilities.[1] Also, fuzing for these new payloads is typically more complicated and expensive. When fuze malfunctions or payload-induced flight instabilities occur, lengthy and costly test programs are required. Normally, these flight tests return only small amounts of information such as payload/fuze function time, range, and time of flight. Custom-built telemetry systems can be employed to provide more detailed information, but such payloads are difficult to develop, are very expensive, and are normally lost after only one test flight. It was recognized that a full scale, three-degree-of-freedom flight simulator could save time and funds during the development cycle of projectile components, fuzes, and payloads for spin-stabilized vehicles.

II. REQUIREMENTS FOR A FLIGHT SIMULATOR

The high spin rates (100-250 Hz) and epicyclic pitch/yaw motions typical of spin-stabilized projectiles are unique. Simulations of these flight conditions have been accomplished using a two-degree-of-freedom spin fixture[2] or a small gyroscope.[3] These devices typically operate with scaled projectile/payload models and reduced angular rates, but have been of great value when specific models for payload-induced instabilities are evaluated. However, ad hoc investigations with projectile hardware are not suited to scaled conditions or simplified motions. In order to rapidly separate stable hardware configurations from unstable configurations, realistic motions and frequencies for full scale models must be generated. This would require a very large and powerful flight simulator. It is also clear that a very large flight simulator could be used as a basic research tool in the dynamics of rotating liquids[4] or loose payload components.[5]

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1. *D'Amico, W. P., Jr., and Miller, M. C., "Flight Instability Produced by a Rapidly Spinning, Highly Viscous Liquid," Journal of Spacecraft and Rockets, Vol. 16, No. 1, January-February 1979, pp. 62-64.*

2. *Miller, M. C., "Flight Instabilities of Spinning Projectiles Having Nonrigid Payloads," Journal of Guidance, Control, and Dynamics, Vol. 5, March-April 1982, pp. 151-157.*

3. *D'Amico, W. P., Jr., and Rogers, T. H., "Yaw Instabilities Produced by Rapidly Rotating, Highly Viscous Liquids," AIAA 19th Aerospace Sciences Meeting, January 12-15, 1981, Paper AIAA-81-0224.*

4. *D'Amico, W. P., Jr., Beims, W. G., and Rogers, T. H., "Pressure Measurements of a Rotating Liquid for Impulsive Coning Motion," Journal of Spacecraft and Rockets, Vol. 20, No. 2, March-April 1983, pp. 99-100. (See also AIAA Paper 82-0246, January 1982.)*

5. *Murphy, C. H., "Influence of Moving Internal Parts on Angular Motion of Spinning Projectiles," Journal of Guidance and Control, Vol. 1, No. 2, March-April 1978, pp. 117-122.*

III. DESCRIPTION

A hydraulic/electric flight simulator was built for the US Army by Carco Electronics, Menlo Park, CA. This simulator is shown in Figures 1 and 2 and is located at the Launch and Flight Division of the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD. Arbitrary angular motions for pitch and yaw can be achieved (outer and inner gimbal assemblies are labeled (a) and (b), respectively) within various operational and load limits. A large support tube (labeled (c)) contains all of the rotating parts, which are driven by an electric motor (labeled (d)). Continuous roll rates as high as 200 Hz can be produced. Such spin rates are typical of maximum launch velocities of modern shell. Presently, only steady roll rates or slowly changing roll rates are possible; however, the roll drive motor can draw up to 500 amperes for impulsive spin profiles. A battery system has been designed, and tests are under way to determine the range of possible spin accelerations.

The operational configuration and performance specifications for the flight simulator were developed for a load that would have mass and inertial properties similar to a 155mm projectile (mass = 50 kg, spin moment of inertia = 0.2 $kg{\cdot}m^2$, and pitch (or yaw) moment of inertia = 2.0 $kg{\cdot}m^2$). The frequency response of the flight simulator dramatically increases as the moments of inertia of the load and the support tube are decreased. Accelerations for pitch/yaw as produced by the flight simulator essentially duplicate the actual flight environment since realistic pitch/yaw amplitudes and frequencies are generated. Typical roll decelerations experienced during flight (for stable shell) do not exceed 10 rad/s^2, and such a roll history can be produced by the simulator. However, roll accelerations experienced during the launch phase are not realistic. For example, the nominal radial acceleration for a projectile during the launch phase is 30,000 rad/s^2 (for a muzzle velocity of approximately 300 m/s). The maximum operational characteristics of the present electric motor with a proposed battery system will only produce accelerations of 100 rad/s^2 for a spin moment of inertia (I_x) of 0.2 $kg{\cdot}m^2$. A reduction in I_x (which is easily accomplished for the flight simulator) would easily result in higher roll accelerations. Even if I_x = 0.02, the roll acceleration would only approach 1,000 rad/s^2, however.

As seen in Figure 1, a gimbal arrangement typical of a gyroscope was selected. This provided several operational and safety features. Since each gimbal drive is independent, hydraulic or command failures simply result in an undesired motion. The support tube (labeled (c) as shown in Figure 2) can accommodate a load with a maximum outer diameter of 0.2 m and a maximum length of 1.0 m. A maximum peak-to-peak motion of 30 degrees is possible, but both hydraulic and mechanical limiters provide for safe operation of the simulator and/or payload components. A large variety of operating conditions are possible; the following table lists typical operating conditions for the largest load and support tube. Projectile flight Mach numbers are included as a link between simulator operating conditions and actual flight conditions.

Mach Number	Angle of Attack (deg)	Pitch (or Yaw) Frequency (Hz)	Roll Frequency (Hz)
0.9	7.5	10.0	100.0
1.2	4.0	15.0	150.0
2.0	1.5	20.0	200.0

A schematic of the operational modes and supporting equipment for the flight simulator is given in Figure 3. The flight simulator can be operated in either a digital or analog command mode. Simple motions can be generated by the input of sine waves to each of the hydraulically driven gimbals. For example, if each of the sine waves are of equal amplitude and frequency, but are out of phase by 90 degrees, then circular coning motion will result. Complicated or arbitrary motions can be generated using digital to analog conversion from a VAX 11/730. This stand-alone minicomputer system is part of the flight simulator facility and is also intended for real time data acquisition as well as command and control. In an effort to produce unique motions for specific payload configurations and to isolate the minicomputer for other tasks, a 16-bit microprocessor system is presently under construction at BRL. This microprocessor will be structured into command and read tables. It will be linked to the minicomputer through a direct memory access (DMA) channel. The VAX 11/730 minicomputer system is also networked to a larger VAX 11/780 minicomputer for off-line data storage, processing, and display.

A 32-channel, Freon-cooled slip ring can be mounted to the top of the support tube (not shown in Figures 1 or 2). This slip ring can be used to pass electrical signals to and from the rotating parts. It is capable of supplying DC power to instrumentation type transducers, thus eliminating any requirement for batteries on the rotating frame. Also, the signal-to-noise ratio is acceptable for instrumentation-type transducer outputs. The speed-range of this slip ring is far above the present spin frequency of the roll drive.

A unique mounting system was designed to position the support tube with respect to the inner gimbal. Figure 2 gives a detailed view of the support tube (labeled (c)) and a wedge ring assembly (labeled (e)) that fixes the support tube to the inner gimbal. The inner surface of the wedge ring has an eight-degree wedge angle that is forced into a ground surface on the support tube. As the wedge ring is drawn down by the bolts, elastic deformation occurs and sufficient forces are generated to fix the support. Hence, the center of gravity of the support tube/spinning parts can be easily changed or located at a variety of positions within the inner gimbal.

The performance characteristics of the simulator can be vastly improved if smaller loads and shorter support tubes are employed. Several shorter support tubes are under fabrication and are intended for smaller test loads to avoid critical speed and bending problems (which would be encountered due to the high roll rate capability). These new tubes will also allow for variations in center-of-gravity positions and will facilitate the assembly and pretest of payload and instrumentation systems.

Figures 4 - 7 give additional details for the flight simulator system. Figure 4 shows the command console and roll drive power supply. Figure 5 shows the hydraulic pump units for the pitch/yaw gimbals (a sound-proof enclosure has been constructed for these units). Figure 6 shows the filter/accumulator system. Figure 7 shows a dynamic balancing machine (capacity of 150 kg) which is located in the flight simulator facility.

IV. SUMMARY

A flight simulator for spin-stabilized projectiles has been built and is operational. It has been configured as the center of a stand-alone test facility complete with dynamic balancing equipment, data acquisition systems, and dedicated computer support.

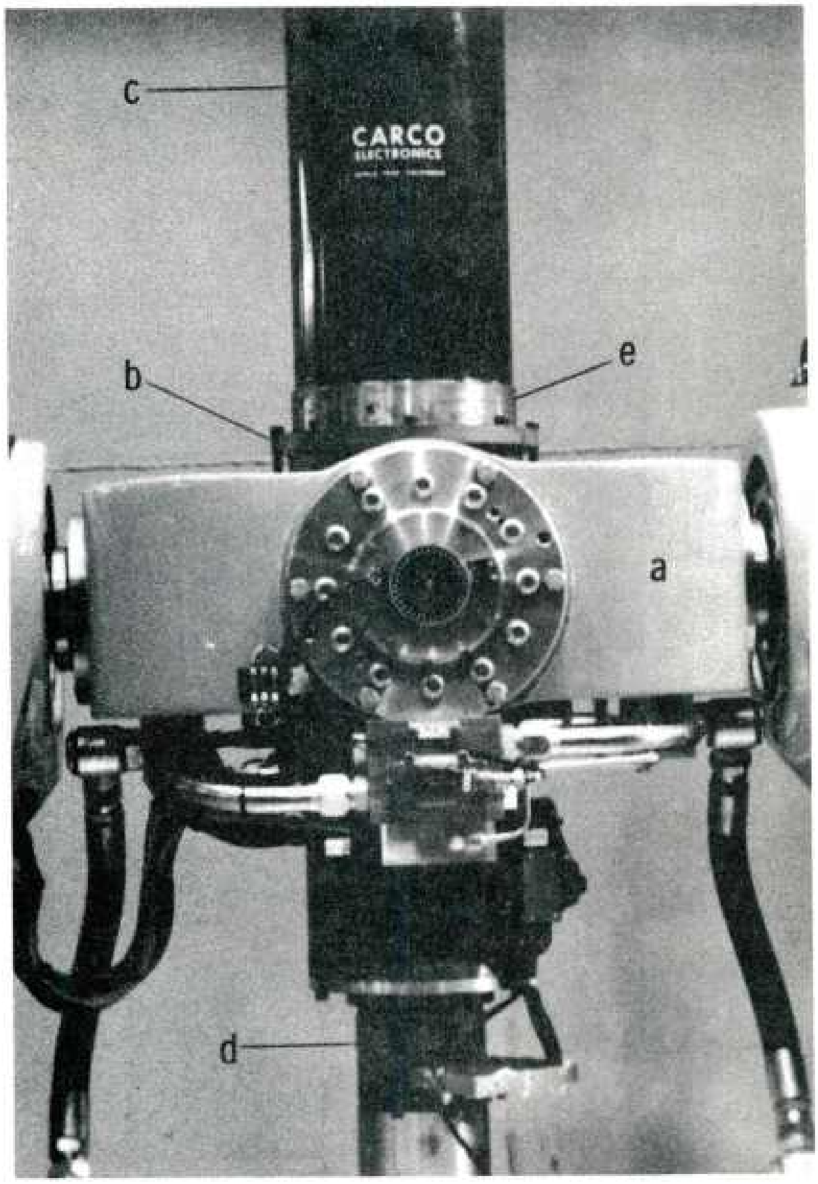

Figure 1. Flight Simulator.

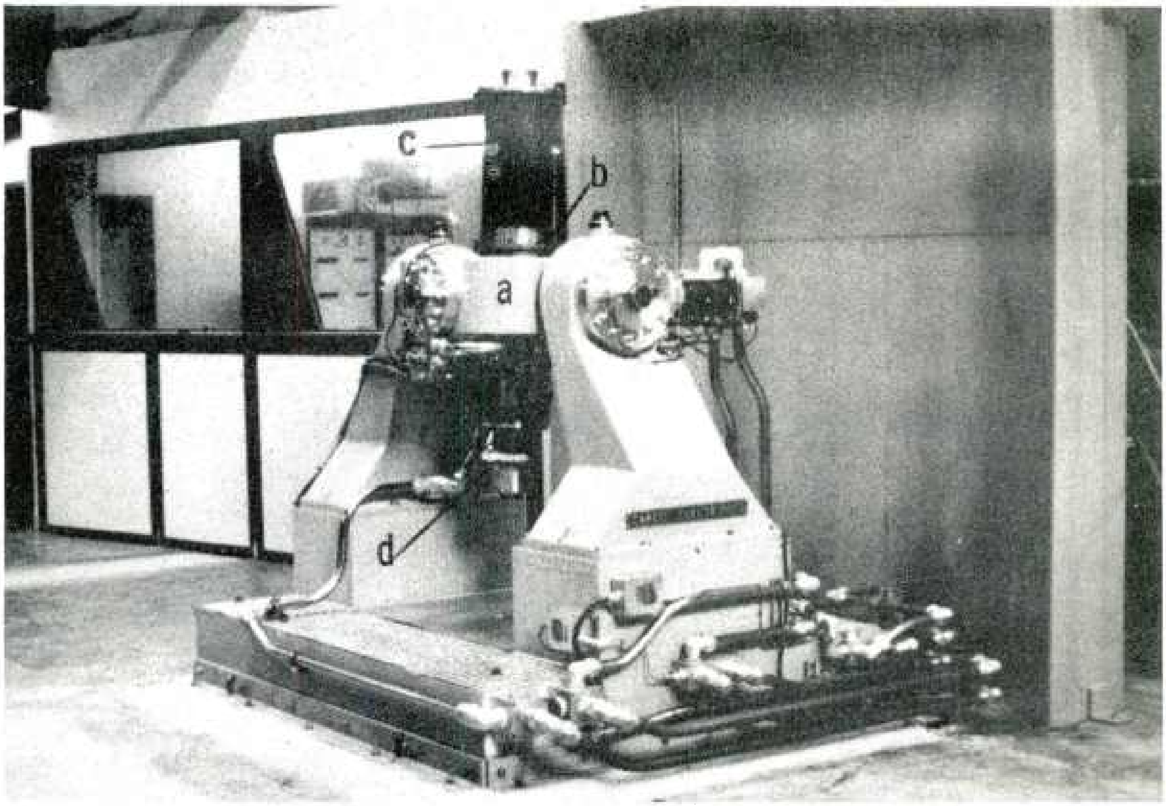

Figure 2. Detailed View of Flight Simulator.

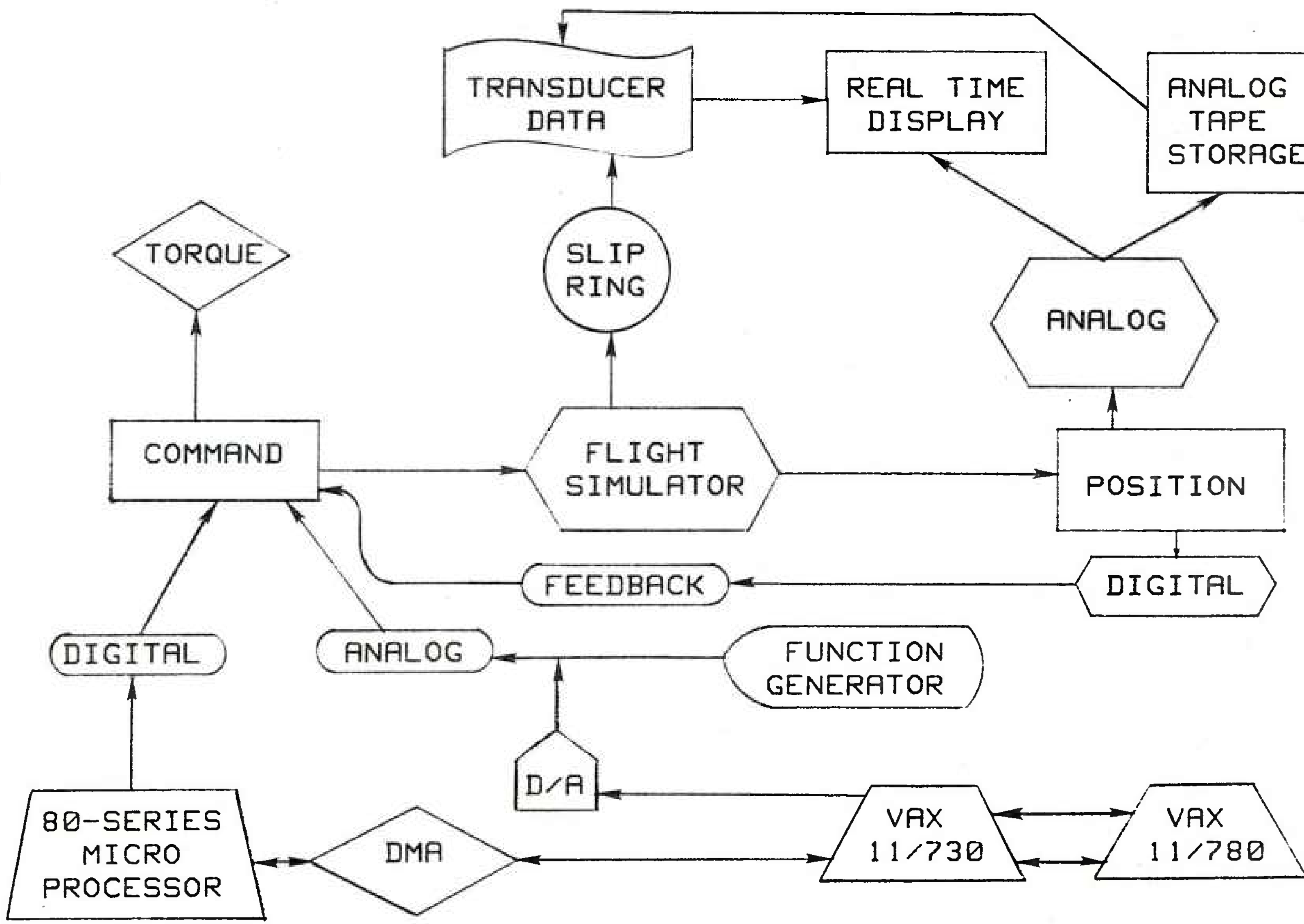

Figure 3. Flight Simulator/Support Equipment Flow Chart.

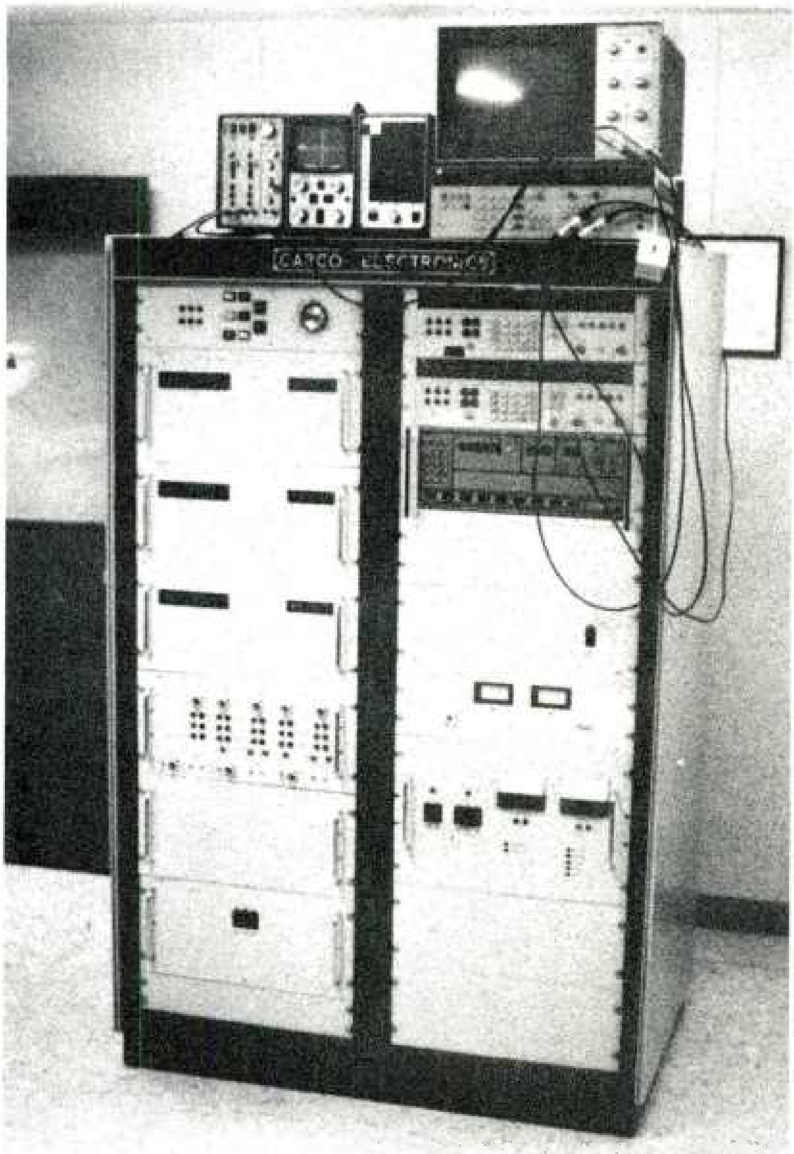

Figure 4. Control Console and Roll Power Supply.

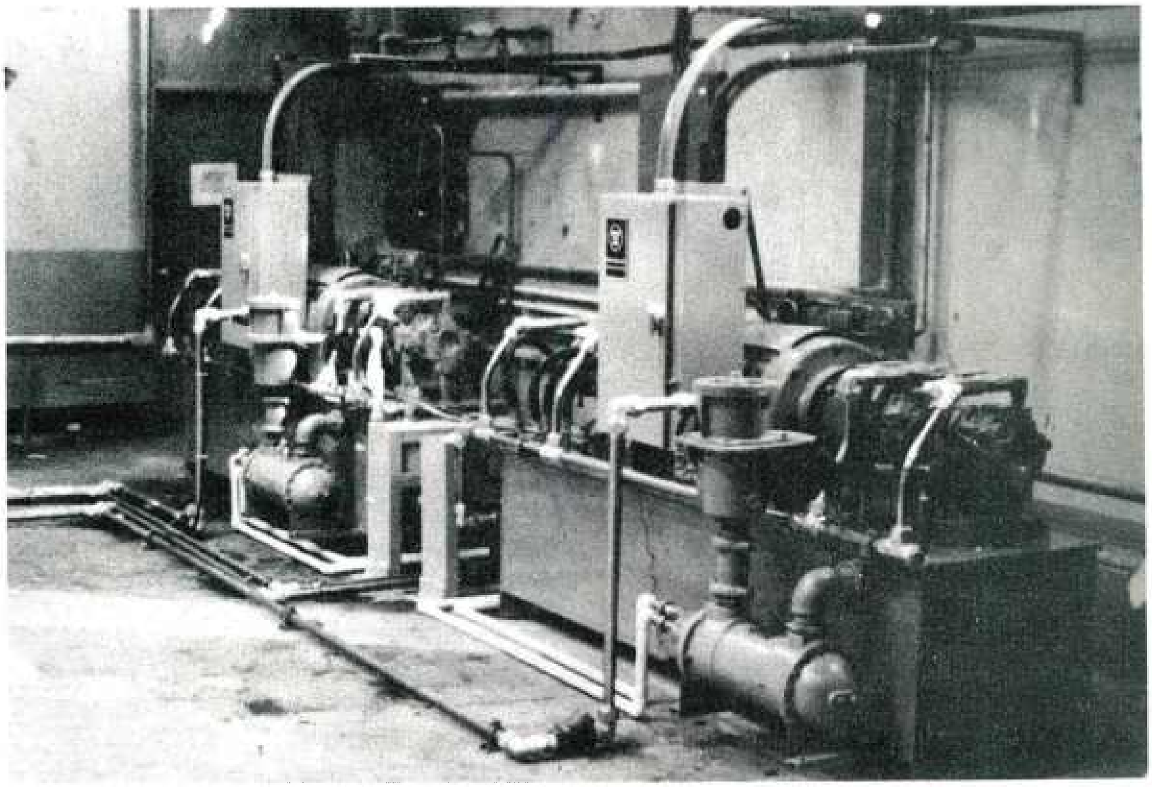

Figure 5. Hydraulic Units for Pitch/Yaw Gimbals.

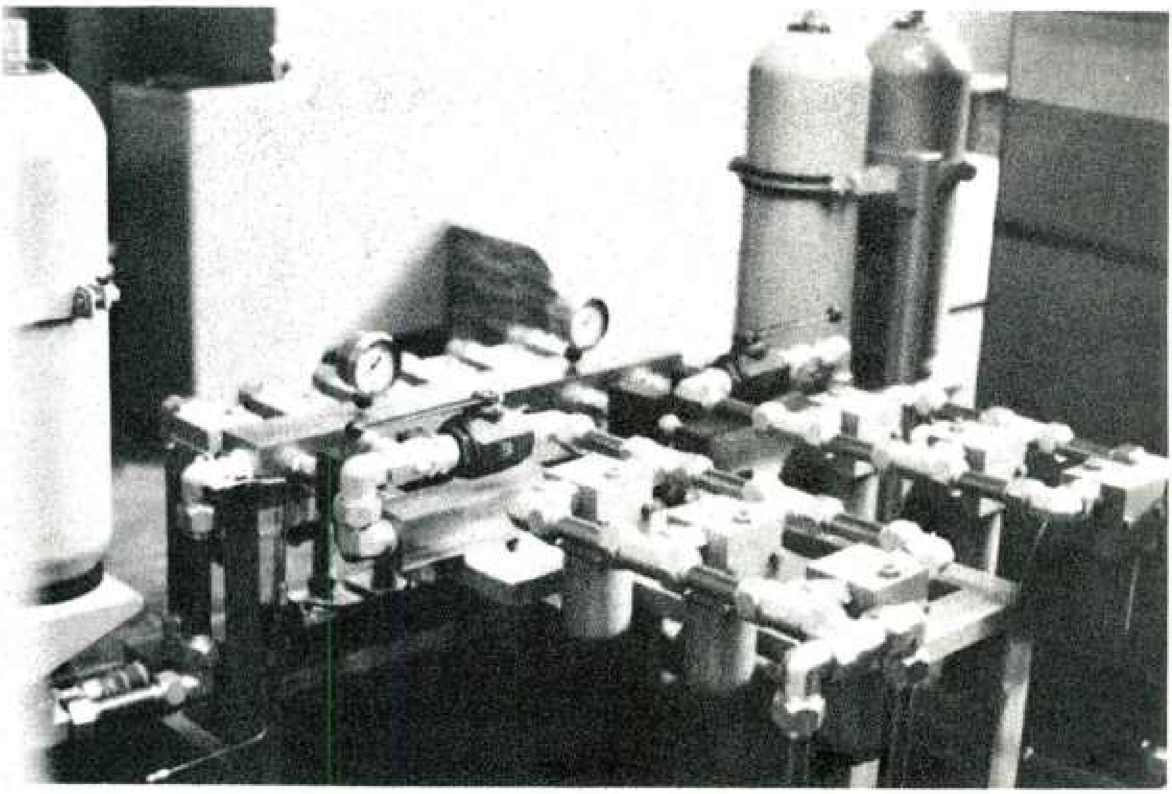

Figure 6. Filters and Accumulators.

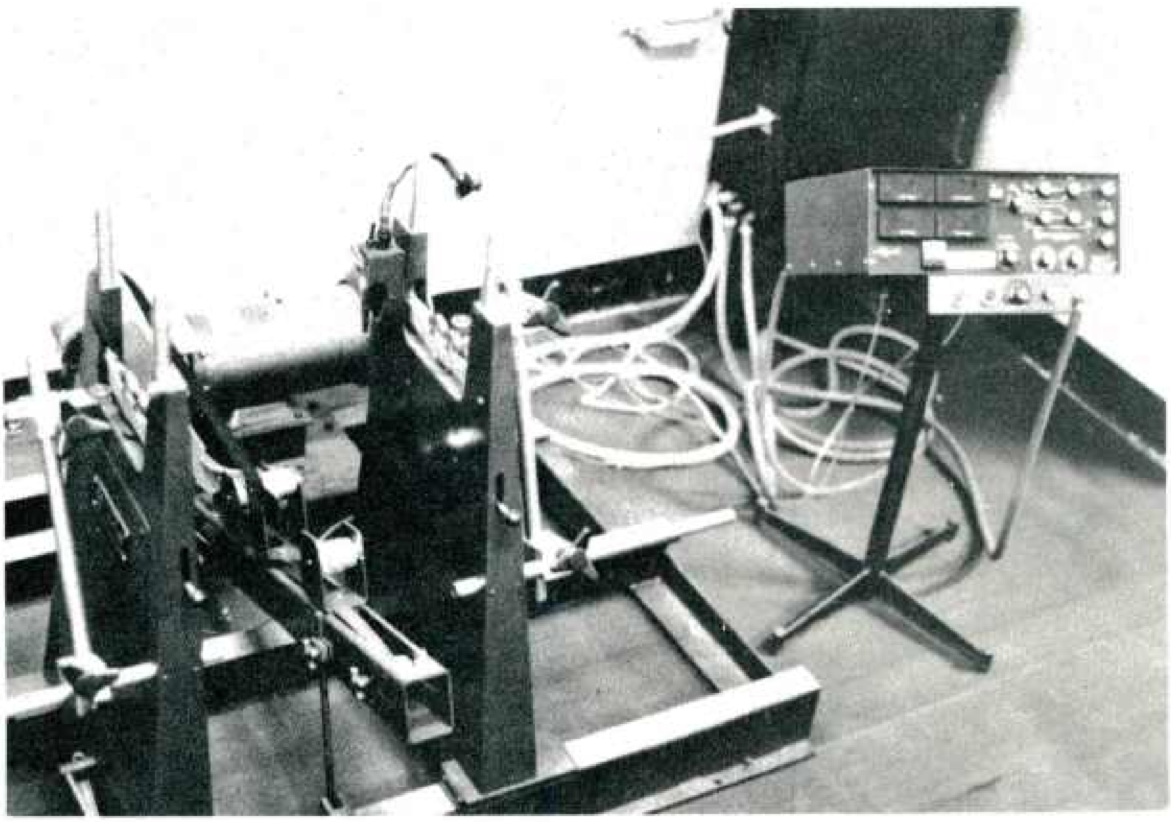

Figure 7. Dynamic Balancing Machine.

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